Combined Piled Raft Foundation (CPRF) System for Polymerization Loop Reactor Structure

P. Jayarajan and K. M. Kouzer

Abstract The current practice followed in the detailed engineering of foundations for critical industrial structures ignores the contribution of the raft (pile cap) and assumes that the loads are supported entirely by the piles. This approach would result in unduly conservative and uneconomical design where the settlement is reduced smaller than necessary with the use of significantly higher numbers of piles. In a combined piled raft foundation (CPRF), the pile cap provides a significant proportion of the required load capacity with the piles strategically placed to boost the performance of foundation by acting as settlement reducers. The paper presents a detailed step-by-step procedure for the implementation of a CPRF as a cost-effective and technically competent foundation system for a polymerization loop reactor structure which represents a critical component of polymerization plant in the refinery unit. The design process consisted of an initial stage of geotechnical site characterization and computation of required parameters based on the results of soil investigation report prepared for detailed engineering. The structural analysis was then undertaken for various code-prescribed critical load combinations to compute the support reactions for foundation analysis and design. The feasibility and further preliminary assessment of CPRF layout was done using Poulos-Davis-Randolph (PDR) method. The pile numbers, length and locations were then refined using finite element-based geotechnical program, PLAXIS 2D. It was found that the implementation of a CPRF versus a conventional piled only foundation provided the required strength and serviceability performance while delivering a cost saving in the order of 30–50%.

Keywords Piled raft · Foundation · PLAXIS

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1 Introduction

Combined pile–raft foundations (CPRFs) are composite structures consisting of three bearing elements: piles, raft, and subsoil. They are normally used in two situations. In the first, piles are necessary for the consideration of bearing capacity, and taking into account the soil below the raft would lead to a reduction in the number of piles. In the second, piles are added below the raft system at strategic locations to control the total and differential settlements. The study of CPRF systems consists of various interactions, namely pile–soil–pile, raft–soil and pile–soil–raft interaction.

Current knowledge in the piled raft foundations allows the engineers to use it as an economical and efficient foundation system, in particular for high-rise buildings. Poulos et al. (2011) provide design guidelines for such foundations. Poulos and Bunce (2008) detail the analysis and design procedure of the piled raft system used in Burj Dubai, the world's tallest building. Poulos (2001) has demonstrated the economy and effectiveness of a CPRF in comparison to pile foundations through the case study of a high-rise building in Australia.

A number of methods are available for the analysis of piled raft foundation systems. Randolph (1994) provides a detailed review of various design methods applicable for a piled raft considering the load levels at which the piles are designed and their primary role in a CPRF. Poulos (2001) presents an approximate method of numerical analysis for piled raft foundations, which predicts well both the settlement behavior and the design loads on piles.

Phung (2010) provides a detailed account of the various finite element tools that are capable of modeling complex soil–pile–raft interactions. Finite element commercial programs such as FLAC 3D, ABAQUS 3D and PLAXIS 3D provide a good means of analyzing piled raft foundations considering the interaction between various elements. A parametrical study of piled raft was performed by Jayarajan and Kouzer (2015) using PLAXIS 3D software.

Experimental investigations also help to provide a better understanding of various factors that govern the performance of CPRF. Jaymin et al. (2016) carried out an experimental study on behavior of piled raft foundation system in sandy soil under vertical load and concluded that the number of piles underneath the raft had a significant effect on the load–settlement relationship. Further, the efficiency of piled raft foundation system in reducing settlement is minimal beyond a certain number of piles. Rasouli et al. (2015) carried out experimental centrifuge modeling to investigate the performance of connected and non-connected pile–raft systems on the load–settlement behavior. The results showed that where the purpose of using piles is to decrease the settlements, the non-connected pile–raft system performs better than the connected system.

2 Problem Definition

The detailed engineering consultants for petrochemical, refinery, and similar plants use either a raft or pile foundation system for critical industrial structures. This approach is unduly conservative and uneconomical. Though there is an increasing demand of combined piled raft foundations for high-rise structures, their use is very limited for critical structures in engineering plants. The above limitation is mainly due to the reluctance of design engineers in adopting a new foundation system in the absence of well-defined design guidelines. The broad objective of the paper involves explaining the step-by-step procedure involved in the sizing and detailed design of combined piled raft foundations for critical structures in engineering plants.

The paper describes the process of design of a piled raft foundation for a polymerization loop reactor structure which represents a critical component of polymerization plant in the refinery unit. The design process comprised an initial stage of geotechnical site characterization using the results of geotechnical investigation which is carried out as a part of detailed engineering. The geotechnical parameters for raft and pile design were then derived. Following this a preliminary foundation analysis was undertaken using the Poulos–Davis–Randolph (P–D–R) method for the loads obtained from analysis of the superstructure to assess the viability of such a foundation system and any potential advantages of a piled raft over conventional fully piled foundation systems. Finally, a detailed analysis was undertaken using the PLAXIS 2D (PLAXIS 2D Version 2002) finite element computer program. The results available from detailed analyses were used to finalize a more efficient piled raft system and to provide design actions for structural design of the foundation system for a variety of load combinations.

3 Description of Structure

Polypropylene unit is the main process unit of the naphtha cracker plant, and the structure for loop reactors represents a critical item in the unit. The loop reactor structure essentially consists of an RCC table top with the main reactors directly supported on it. The steel structure is essentially braced in one direction with the moment-resisting frames provided in the other. The loop reactors along with a part of the steel structure are in the scope of equipment supplier. The topmost steel platform attached to the reactor structure is at an elevation of 55 m above the ground. A pictorial view of the structure is given in Fig. 1.

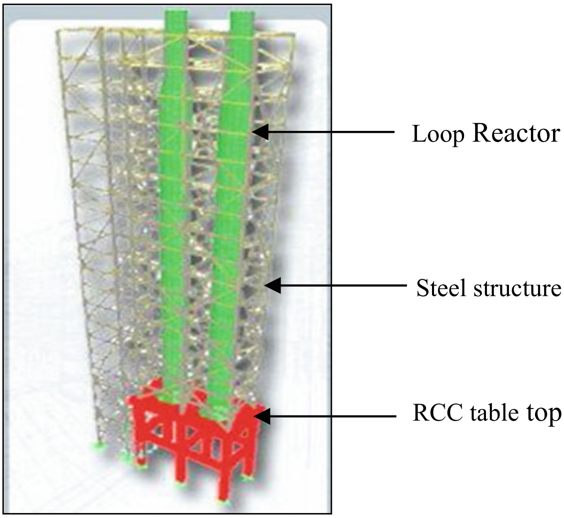


Fig. 1 3D view of loop reactor structure

4 Geotechnical Conditions

In the job site the subsoil is alluvial in nature and consists of stiff sandy clayey silt to a depth of about 12.0 m from existing ground level with N values of 10–15 (layer-1a). The top layer is underlain by very stiff sandy clayey silt from 12 to 18 m with N values of 20–40 (layer-1b). From 18 m to termination depth of bore holes dense silty sand is observed with N values of 50–70 (layer-2). Based on the ground water levels measured in boreholes, the ground water level has been considered at 2.0 m below the ground level. Standard penetration tests (SPTs) have been carried out in the site at different depths in various locations. The summary of various geotechnical parameters derived from the empirical correlations with the SPT values is given in Table 1.

Table 1 Geotechnical parameters

Strata	N	γ	C_u or ϕ	E_u	E
1a	10–15	18	50–75	10–15	7–10
1b	20–40	20	100–200	20–40	15–30
2	50–70	20	38°	–	40–50

N = Standard penetration values
γ = Bulk unit weight (kN/m^3)
C_u = Undrained shear strength (kN/m^2)
ϕ = Angle of internal friction (degrees)
E_u = Undrained Young's modulus (kN/m^2)
E = Long-term drained Young's modulus (kN/m^2)

Table 2 Load combinations for foundation assessment

S. no.	Serviceability limit state	Ultimate limit state
1	DL + OP + LL	–
2	DL + OP + WL	–
3	DL + OP + 0.9LL + 0.9WL	–
4	–	1.35DL + 1.35OP + 1.35LL
5	–	1.35DL + 1.35OP + 1.5WL
6	–	1.35DL + 1.35OP + 1.35LL + 1.35WL

As per the geotechnical recommendations for the job site, shallow foundations on the stiff sandy clayey silt stratum may be used for structures subjected to limited static loads. However, for structures subjected to dynamic loads or large static loads and for those structures which are sensitive to settlements, pile foundations are recommended.

5 Loading and Structural Analysis

For the polymerization loop reactor structure, the critical load data for loop reactors at their support bases (8 nos.) is normally provided by the reactor vendor. Further, the support reactions from the vendor-supplied steel structure are also available. The basic loads considered for the analysis include dead load (DL), operating load (OP), live load (LL), and wind load (WL). The wind loads are considered in each of the two mutually perpendicular directions. Earthquake loads are not considered as they were not critical. The load combinations used for foundation assessment include both serviceability limit states (SLS) and ultimate limit states (ULS). The summary of critical load combinations taken from detailed project design specifications is given in Table 2. The structural analysis was performed using the STAAD-Pro software for basic loads and load combinations. A 3D analysis model for the structure is shown in Fig. 2.

6 Foundations Loads

The foundation loads are calculated at column locations for critical load combinations. The column layout is shown in Fig. 3. The layout basically consists of two rows of columns 7 m apart, their spacing being 4.2 m. The resultant column loads and moments transferred from superstructure to the foundation corresponding to the

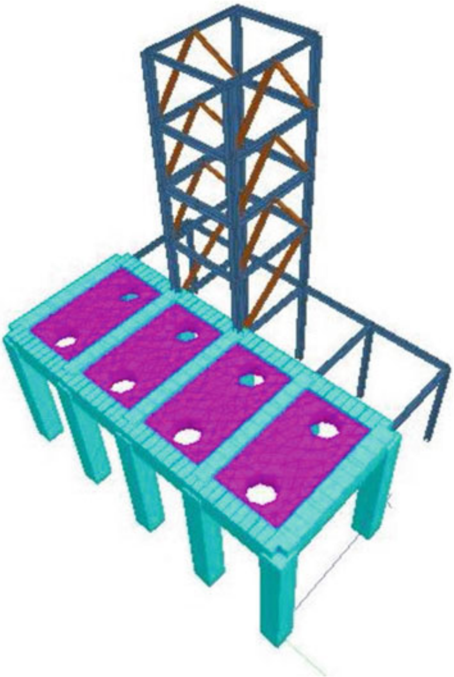


Fig. 2 3D structural analysis model

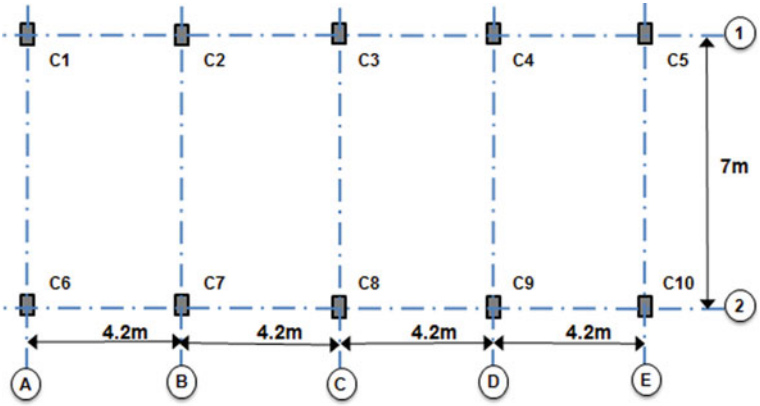


Fig. 3 Structural column layout

Fig. 4 Foundation loads from superstructure

most critical serviceability limit state are represented in Fig. 4. The review of loads indicates that the foundation is subjected to large eccentric loads.

7 Preliminary Foundation Assessment

Prior to the detailed foundation assessment, a feasibility study was conducted for various foundation schemes. The foundation assessment was carried out for (a) a raft alone without pile, (b) conventional pile foundation, and (c) combined piled raft foundation. For preliminary assessment, 450 mm diameter-driven cast in situ piles of 18 m length were considered. Based on previous experience with similar structures and considering adjacent constructions, a rectangular raft of size 20 × 10 m and 1.2 m thick was considered. The bottom of raft was kept 2.0 m below the ground level. The conclusions are presented in the following sections.

7.1 Raft Alone Without Piles

Considering the self-weight of raft and foundation soil and applying basic principles of engineering mechanics, the foundation loads shown in Fig. 4 could be represented by an equivalent load of 22460 kN at an eccentricity of 1.25 m. The modeling and detailed analysis of the raft foundation was done using finite element program PLAXIS 2D with a plane-strain model. The soil was represented using Mohr–Coulomb material model and raft by linear elastic material. The material properties used in the analysis are listed in Tables 1 and 3. The plane-strain model of the raft is shown in Fig. 5 and the deformed mesh in Fig. 6.

The load–settlement curve obtained from PLAXIS calculations is shown in Fig. 7. It was concluded from the above calculations that the raft foundation alone would

Table 3 Material properties used in PLAXIS analysis

Parameter	Raft	Piles
Material behavior	Elastic	Elastic
Axial stiffness (kN/m)	30E6	1.8E6
Bending stiffness(kNm^2/m) Poisson's ratio	3.6E6 0.25	2.3E4 0.25

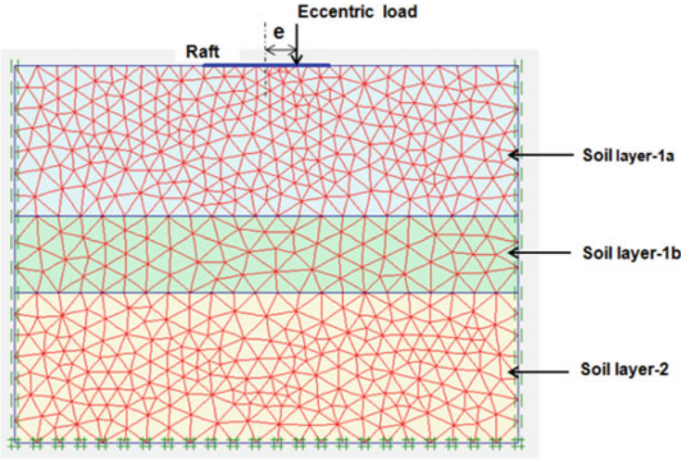
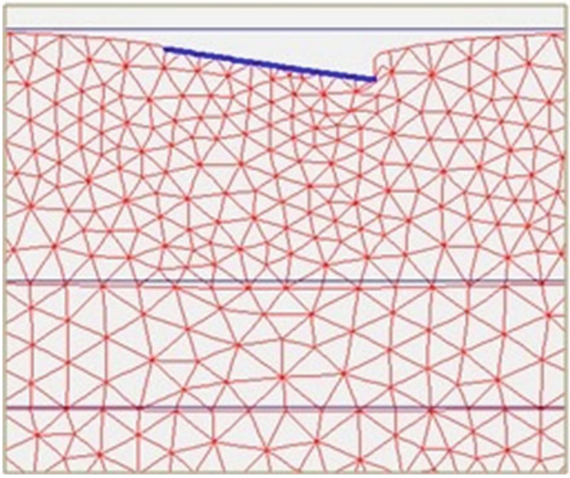


Fig. 5 Plane-strain model for the raft

Fig. 6 Deformed finite element mesh (raft)



have an overall safety factor of 2.0 under extreme wind loads and more than 3.0 under dead, operating, and live loads. However, the calculated maximum foundation settlement of 120 mm is much higher than the allowable value of 40 mm provided in project design specifications. Further, the calculated angular distortion of 1 in 140 is much higher than permissible value of 1 in 500. Therefore, the foundation design would be governed by the settlement and tilt considerations rather than by the ultimate bearing capacity.

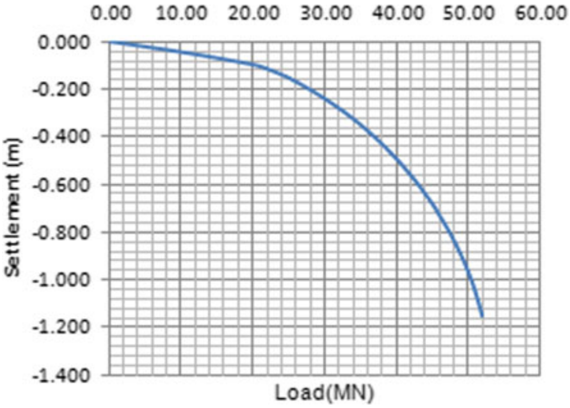


Fig. 7 Load versus settlement curve for raft

7.2 *Pile Foundation*

A preliminary assessment has shown that 45 numbers of 18 m long piles would be required as in the pile layout shown in Fig. 8. The pile foundation is modeled as a plane-strain model in PLAXIS 2D. The piles and raft were modeled using plate elements. The out of plane row of piles is modeled as plane-strain piles with an equivalent pile modulus of deformation in terms of the number of piles in the row considering the dimension of the pile and that of the raft. The interface strength coefficient R_{inter} in the model is adjusted so that the plane-strain piles develop the same shaft resistance of actual piles in the row. The plane-strain model of the pile foundation is shown in Fig. 9 and the deformed mesh in Fig. 10.

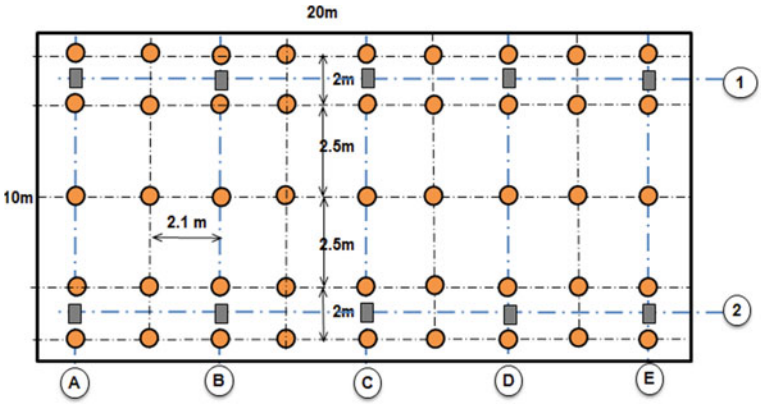


Fig. 8 Foundation pile layout (45 nos. of piles)

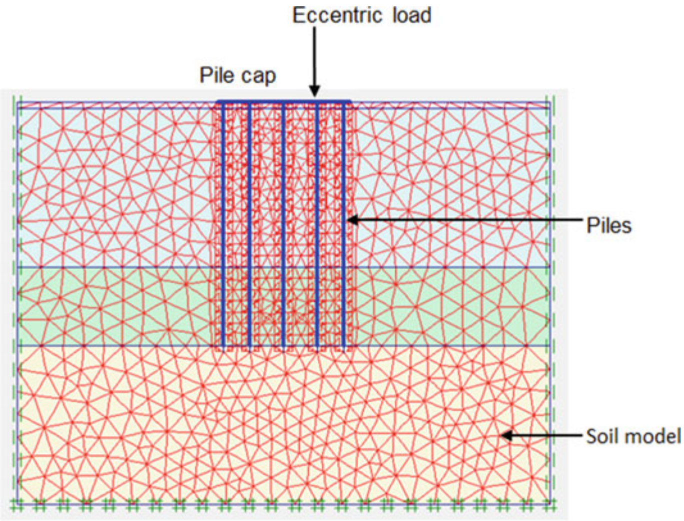


Fig. 9 Plane-strain model of pile foundation

Fig. 10 Deformed finite element mesh (piles)

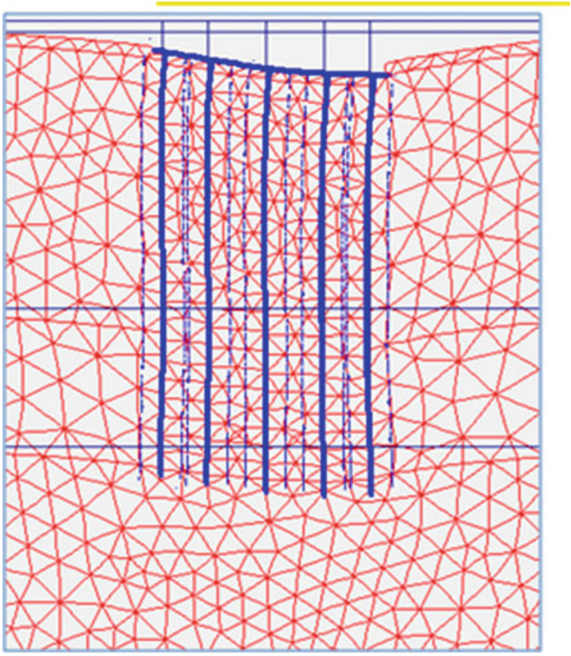
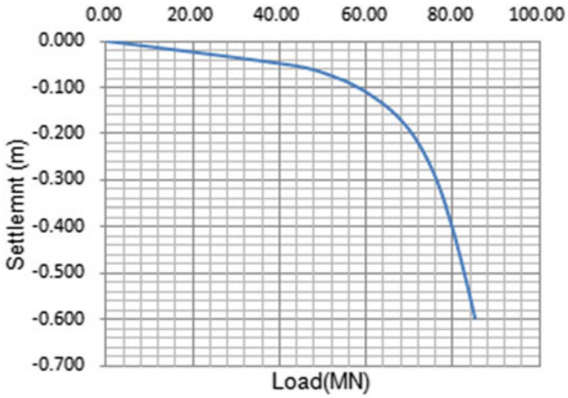


Fig. 11 Load–settlement curve for pile foundation



The load–settlement curve obtained from PLAXIS calculations is shown in Fig. 11. It was concluded that the pile foundation with 45 numbers of piles would have an overall safety factor of 4.0 under extreme windloads and the calculated maximum foundation settlement of 23 mm is well within the acceptable limits of 40 mm. Further the angular distortion of 1 in 900 is much less than permissible value of 1 in 500. Considering that the pile arrangement has excess capacity in terms of strength and serviceability, the possibility of using a combined piled–raft foundation is investigated with lesser number of piles.

7.3 Combined Piled–Raft Foundation (CPRF)

The behavior of a piled–raft foundation is determined by the interactions between the piles, raft, and soil. In reality, there are two basic interactions, pile–soil–pile interaction and pile–soil–raft interaction, as shown in Fig. 12. The feasibility of using a piled–raft is assessed using Poulos–Davis–Randolph (PDR) method. The method provides the number of piles to satisfy the design requirements relevant to strength and serviceability.

The simplified representation of piled–raft as used in PDR method is shown in Fig. 13. As per the method, the stiffness of the piled raft foundation can be estimated as:

$$Kpr = \frac{((Kp + Kr(1 - \propto cp)))}{\left(1 - \alpha cp^2 * \frac{Kr}{Kp}\right)} \tag{1}$$

where Kpr = stiffness of piled raft; Kp = stiffness of the pile group; Kr = stiffness of raft alone; αcp = raft–soil–pile interaction factor.

The proportion of the total load carried by the raft is

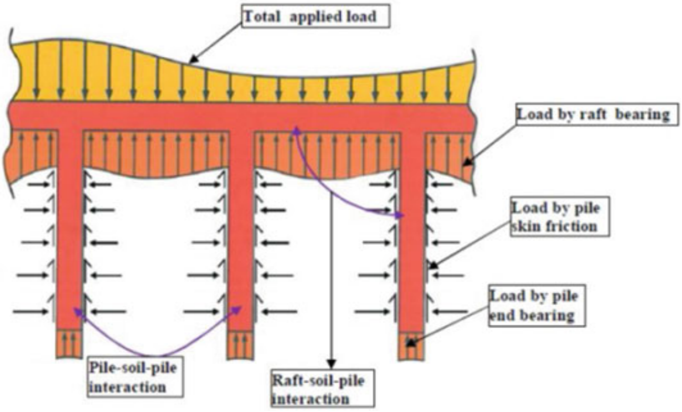


Fig. 12 Interactions in a piled raft foundation

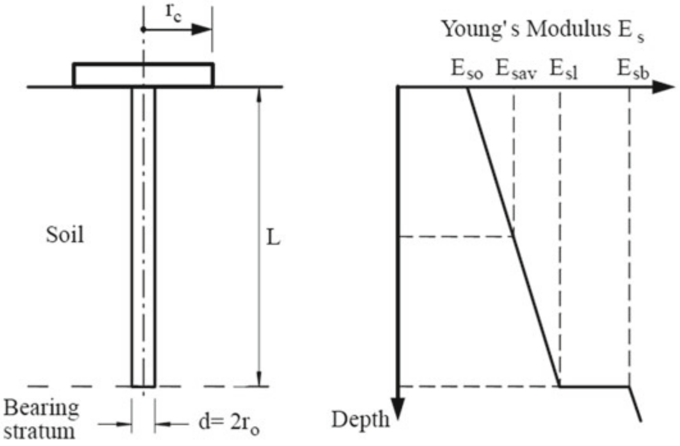


Fig. 13 Simplified representation of a piled raft unit

$$\frac{Pr}{Pt} = X = \frac{Kr(1 - \alpha cp)}{Kp + Kr(1 - \alpha cp)} \tag{2}$$

where Pr = load carried by the raft; Pt = total applied load.

If Pup is the ultimate load capacity of piles in the group, total load on the foundation at which the pile yields is given by

$$P1 = Pup/(1 - X) \tag{3}$$

The pile–soil–raft interaction factor αcp can be estimated as follows:

$$acp = 1 - \ln\left(\frac{rc}{r0}\right) \Big/ \beta \tag{4}$$

where rc = average radius of pile cap (corresponding to an area equal to the raft area divided by number of piles); r0 = radius of pile; $\beta = \ln(rm/r0)$; ν = Poisson's ratio of the soil; $rm = \{0.25 + \xi[2.5\rho(1-\nu) - 0.25]\} * L$; $\xi = Esl/Esb\rho = Esav/Esl$; L = pile length; Esl = soil Young's modulus at level of pile tip; Esb = soil Young's modulus of bearing stratum below pile tip; Esav = average soil Young's modulus along pile shaft. A tri-linear load–settlement curve developed using the above equations is shown in Fig. 14.

The preliminary CPRF arrangement as shown in Fig. 15 is used to support the design loads. The CPRF considered consists of the raft of the same size but supported by lesser numbers of piles compared to the pie foundation. A total of 25 numbers of piles each of length 18 m is considered for the study. The calculations done using the

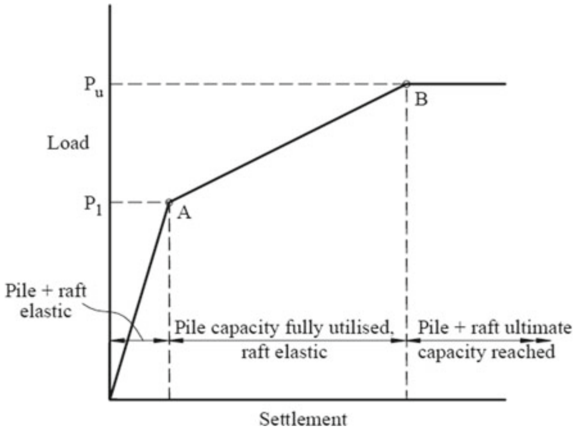


Fig. 14 Simplified load–settlement curve of CPRF

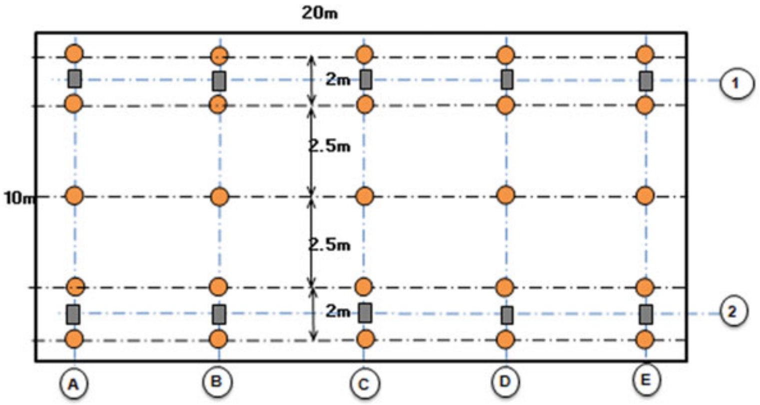


Fig. 15 Combined piled raft—pile layout (25 nos.)

MATHCAD worksheet developed by the authors give P1 = 52468 kN, Pu = 104538 kN. Further, the settlement of 29.4 mm corresponding to a service load of 22460 kN is acceptable.

It shall be noted that the preliminary calculations using PDR method assumes a concentric load conditions. Accordingly, detailed assessment shall be done for the actual applied eccentric loads to understand the load transfer mechanism and the load–settlement characteristics.

7.4 Recommendations from Preliminary Geotechnical Assessment

Based on the results of the preliminary geotechnical assessment, it was recommended that a combined piled raft foundation system should provide a cost-effective solution for the foundations of polymerization loop reactor structure with required safety on strength and settlement.

8 Detailed Foundation Calculations

Based on the preliminary assessment, detailed calculations were done for CPRF layout shown in Fig. 15 using PLAXIS 2D. The thickness of the piled raft was considered same as 1.2 m. The water table has been modeled at 2.0 m below the ground level. A plane-strain model was considered for the analysis and computation of design forces in various elements. The deformed mesh of CPRF model is shown in Fig. 16. Two cases of loading were considered first with a concentric load system and the other with an eccentric loading. These cases were studied for the purpose of comparison with PDR method and also to examine the effect of load eccentricity on CPRF. A comparison of PDR method with PLAXIS analysis is shown in Fig. 17. It can be seen that behavior is almost the same in the linear portion corresponding to the development of full pile capacity and deviation is significant in the nonlinear portion. As the CPRF under consideration is subjected to highly eccentric loads, its behavior is also reviewed at different eccentricities (e = 0, 0.5 and 1.25 m) and the response is given in Fig. 18. As expected, the CPRF capacities decrease with increasing values of eccentricity.

The load–settlement behavior of the CPRF corresponding to applied eccentricity of e = 1.25 m is shown in Fig. 19. It is clear that the CPRF has a factor of safety of much higher than 3.0 under worst loading condition and maximum settlement of 36 mm is within the allowable value of 40 mm. Further, the angular distortion of 1 in 525 is less than permissible value of 1 in 500. Thus, the CPRF with much lesser numbers of piles satisfies the strength and serviceability requirements.

Fig. 16 Deformed finite element mesh

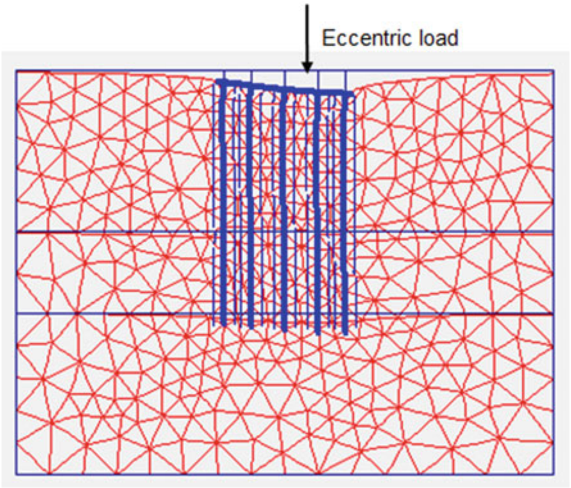


Fig. 17 Comparison of PDR method with PLAXIS

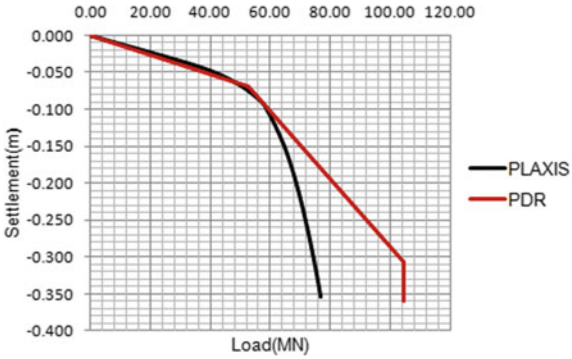


Fig. 18 Response of CPRF to different eccentricities

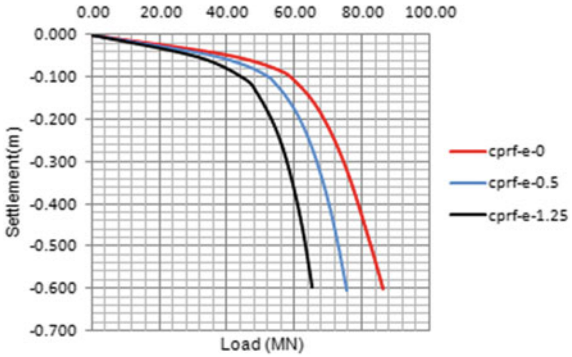


Fig. 19 Load–settlement curve for CPRF

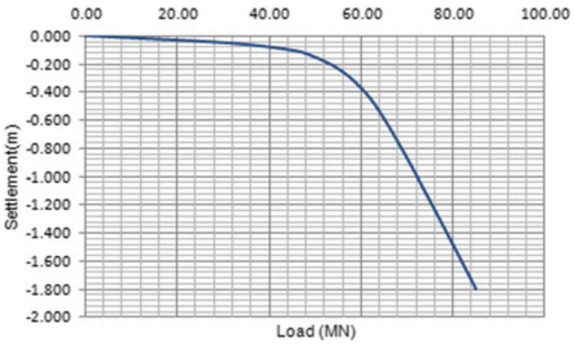
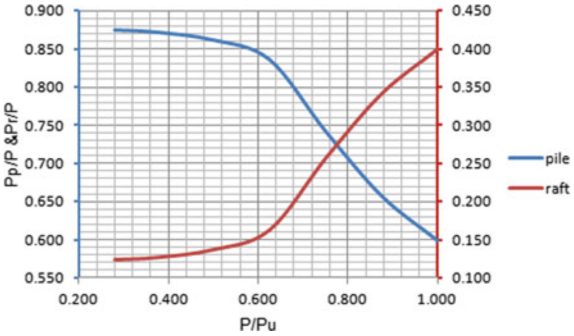


Fig. 20 Load-sharing mechanism for CPRF



It is very clear that the participation of piles takes place at low settlement levels where the raft starts contributing at higher settlements. Thus, the load distributed by raft and pile elements in a CPRF depends upon the settlement levels which are controlled by the applied load. The load sharing mechanism is demonstrated in Fig. 20. P_u = Ultimate load capacity of CPRF, P = applied load which is shared between piles (P_p) and raft (P_r) elements. Finally, a comparison of different foundations considered in the study, namely raft-only, pile-only, and combined raft foundation at an applied eccentricity of e = 1.25 m is shown in Fig. 21.

9 Ultimate Limit State Assessment CPRF

Using the ultimate limit state (ULS) loading combinations provided in Table 2, structural assessment of the piled raft was made. The computed values of maximum and minimum design values for the various structural actions are summarized in Table 4. It can be seen that the structural actions remain almost the same for raft element in CPRF and pile-only foundation. However, the pile loads appear to be much higher in CPRF compared to the pile-only foundation. This is obviously because of the lesser number of piles used in CPRF. Therefore, a part of the saving due to the

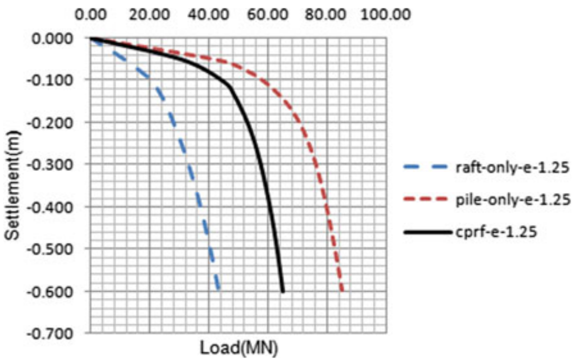


Fig. 21 Performance for reviewed foundations

Table 4 Summary of design actions (ULS)

Parameter	Axial Force (kN)	Shear[a] Force (kN)	Bending[a] Moment (kN m)
(a) CPRF Pile	709	96	158
	1790	75	27
Raft	–	854	2170
(b) Pile-Only Pile	433	64	107
	1184	104	98
Raft	–	851	2074

[a] Raft shear force and bending moments are per meter width

use of lesser number of piles in CPRF will be offset by correspondingly higher pile reinforcement.

10 Conclusions

The paper has provided a detailed procedure for the analysis and design of a combined piled raft foundation (CPRF) for the critical polymerization loop reactor structure in a refinery unit. The procedure involved characterization of soil profile using detailed geotechnical investigations, initial geotechnical assessment of possible types of foundation solutions, namely raft-only, pile-only, and the CPRF, and finally detailed calculations are done to verify the foundation response under critical loads. The objective of the paper is to provide necessary guidelines for detailed assessment of combined piled raft foundations for critical structures. It is expected that the paper will encourage practicing engineers involved in detailed engineering of sensitive and critical structures to come out with an efficient and economical foundation solution.

The Poulos–Davis–Randolph (PDR) method provides an efficient methodology for preliminary assessment of CPRF. The PLAXIS 2D finite element computer program can consider the complex interactions between various elements in a CPRF and provide the foundation response for various load combinations. The program also provides detailed summary of various design actions for ultimate limit state and can be used by structural engineers for design of raft and pile elements.

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